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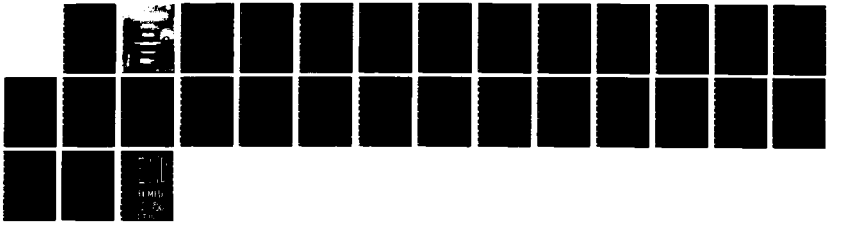

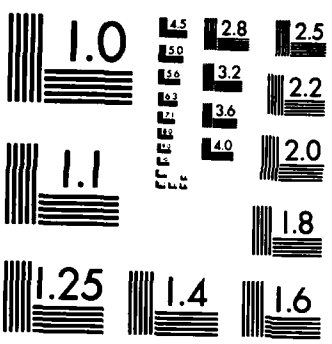

R85-927162-1

INVESTIGATION OF PLASMA PROCESSES IN ELECTRONIC TRANSITION LASERS

Annual Report
December 15, 1985

William L. Nighan
Principal Investigator

Sponsored by The Office of Naval Research
Contract: N00014-85-C-0259

UNITED TECHNOLOGIES RESEARCH CENTER
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United Technologies Research Center is conducting an investigation of the fundamental processes affecting the operation, performance and application of electrically excited lasers having potential utility in a variety of areas of importance to the Navy. Particular attention is presently focused on the broadband XeF(C→A) laser, which has the potential for efficient, tunable operation throughout the blue-green spectral region. The research at UTRC is closely coordinated with a complementary ONR-supported experimental program being conducted at Rice University. This Annual Report summarizes recent results of this investigation, and includes reprints of recently published papers in which specific results and conclusions of the research are described in detail.

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transient absorption in the visible region; rare gas-halide mixture synthesis; efficient XeF(C→ A) laser, tunable visible laser, tunable blue-green laser.

FORWARD

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Investigation of Plasma Processes in Electronic Transition Lasers

TABLE OF CONTENTS

I. SUMMARY OF MAJOR RESULTS

A. Background

The electrically excited, blue-green XeF(C→A) laser has potential for application in several areas of importance to the Navy. Among its advantages are: near optimum wavelength for transmission through sea water without the complexity of frequency shifting; room temperature operation; and, most importantly, potential for efficient tuning throughout the 450-520 nm wavelength range. Until recently, this promising laser suffered from an unacceptably low energy conversion efficiency (i.e. << 1%) when electrically excited, due primarily to the occurrence of severe transient absorption by species present in the laser medium itself. However, progress under the present UTRC program and a collaborative ONR supported program at Rice University resulted in identification of the primary species responsible for the absorption (Ref. 1). Following this development, significantly improved XeF(C→A) laser performance was achieved using electron-beam excitation of multi-component gas mixtures specifically tailored so as to reduce medium transient absorption in the blue/green region (Refs. 1 - 3). Indeed, broadband blue-green laser pulse energy density and intrinsic efficiency values of ~ 2 J/liter and ~ 1-2 %, respectively, have been demonstrated (Ref. 3). This performance level compares favorably with the UV B→X rare gas halide lasers, and additional improvement in the XeF(C→A) laser seems certain. Very recently, efficient narrow spectral output was demonstrated for the first time by injection control of an e-beam excited XeF (C→A) medium (Ref. 4). Additionally, relatively efficient (~ 1%) simultaneous UV/visible laser oscillation on the XeF B→X and C→A excimer transitions was achieved (Ref. 5), and dual wavelength UV laser operation was demonstrated on the ArF/KrF and KrF/XeF B→X transitions oscillating at the same time (Ref. 6).

The progress of the past year has resulted in two publications and several presentations, co-authored with workers at Rice University. The papers are: "Efficient Narrow Spectral Output in the Blue-Green Region from an Injection Controlled Electron Beam Excited XeF (C→A) Laser", Applied Physics Letters, 47, 657 (1985); and "Simultaneous UV/Visible Laser Oscillation on the B→X and C→A XeF Excimer Transitions", IEEE Journal of Quantrum Electronics, QE-21, 418 (1985); both of which are reproduced in Section II of this report.

B. Discussion Of Results

1. XeF (C→A) Laser - Narrow Spectral Output

Very significant improvement in the performance of an electron-beam (e-beam) excited XeF(C→A) laser has been achieved by selective tailoring of the gas

mixture so as to minimize transient absorption (Refs. 1-3). Use of multi-component gas mixtures comprised either of Ar-Xe-F_2-NF_3 or of Ar-Kr-Xe-F_2-NF_3 has resulted in laser pulse energy density values in the 1.5 to 3.0 J/l range with an intrinsic efficiency of approximately 2.0%, a performance level which, for the first time, is comparable to that typical of the B→X rare gas halide and mercury-halide lasers. In these studies the broadband, free running XeF(C→A) laser output was centered at ~ 480 nm with a bandwith of ~ 25 nm (FWHM). However, measurements showed that the net gain extended over a much larger spectral range and that the gain exhibited a relatively weak dependence on wavelength. These results indicate that it should be possible to tune the XeF(C→A) laser continuously throughout the entire blue-green region, with narrow spectral width and with an efficiency typical of that demonstrated in the free running mode.

In an important first step toward efficient spectral tuning, efficient narrow spectral output was demonstrated at Rice University by injection control of the e-beam excited XeF(C→A) laser medium using a 482 nm dye laser pulse (Ref. 4). Using unstable resonator optics to expand the input beam, and with the XeF(C→A) medium functioning as a multipass amplifier, output energy density and intrinsic efficiency levels up to 3 J/liter and 2%, respectively, were obtained Figure 1 shows the dependence of the XeF(C→A) output pulse energy on the energy of the injected dye laser pulse. The linear dependence of the output pulse energy on dye laser input energy for a three order of magnitude variation of the latter indicates that the cavity/medium combination was acting as a multipass amplifier for these conditions, and that the gain is not significantly saturated until high input energies are reached. Such behavior is consistent with the very low output that was obtained with the unstable resonator operating as a free running oscillator. However, saturation of the gain medium appears (Fig. 1) to occur for input pulse energies above approximately 0.1 mJ. The 20 mJ maximum output for the M = 1.23 cavity corresponds to an energy density of ~1 J/l and an intrinsic energy utilization efficiency of approximately 1 percent for these specific conditions. Using a cavity having a magnification of 1.14 energy density and efficiency values of 3 J/l and ~2.5% were obtained; these results are also shown in Fig. 1.

Presented in Fig. 2 is the broadband XeF(C→A) laser spectrum typical of the unstable (or stable) resonators operating as free running oscillators, compared with that of the injection controlled XeF(C→A) amplifier. The indicated ~ 0.5 nm width of the amplified 482 nm dye laser pulse reflects the resolution limit of the measurement system. Preliminary evaluation of the spectral characteristics of the narrowed XeF(C→A) output indicates that the spectral width is nearly the same as that of the dye laser input, i.e., $\Delta\lambda \sim 0.01$ nm.

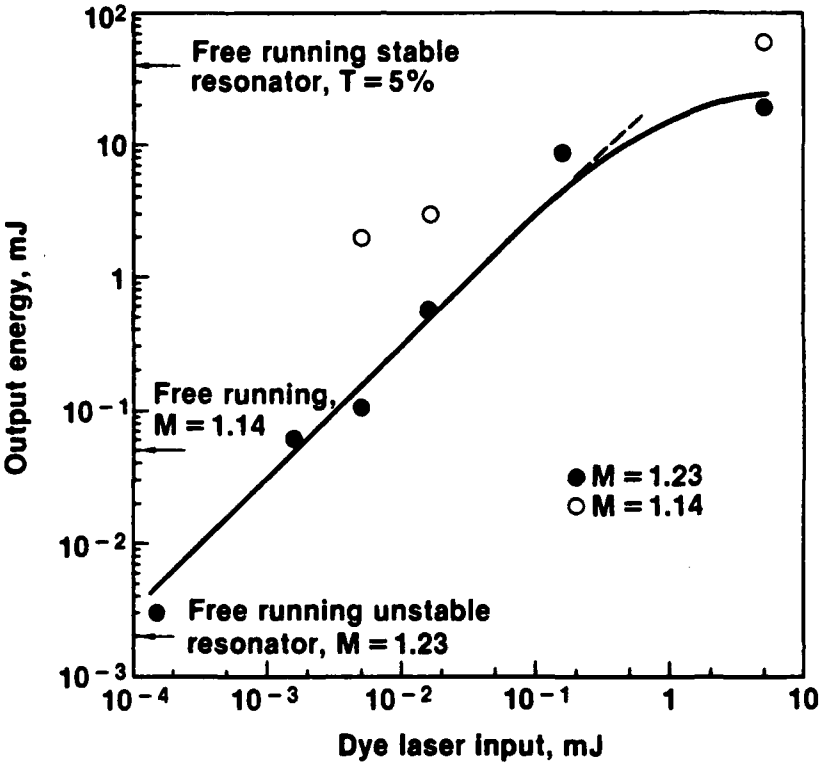

Fig. 1 XeF(C→A) output pulse energy dependence on the injected dye laser energy, both at 482 nm, measured using a calibrated vacuum photodiode detector. The gas mixture was comprised of 6.5 atm Ar, 16 Torr Xe, 8 Torr NF_3, and 8 Torr F_2; and the volumetric e-beam energy deposition was ~ 100 J/l. Laser output levels obtained with unstable and stable (optimized) free running oscillators are indicated (see Sec. II and Ref. 4 for details).

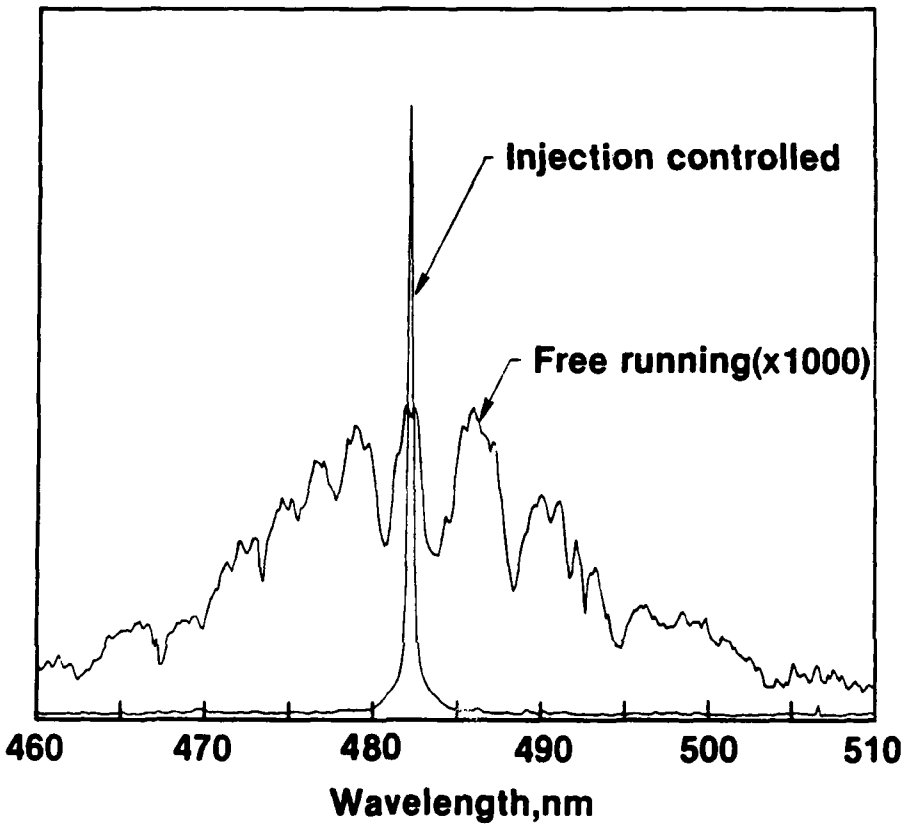

Fig. 2 XeF(C+A) spectra for the free running and injection controlled conditions of Fig. 1. The resolution limit of the measurement system was 0.5 nm.

2. Multiwavelength Laser Operation

a. XeF B→X/C→A Laser Oscillation

In a multicomponent gas mixture optimized for blue-green XeF(C→A) laser oscillation it was found that significant gain also exists for the UV B→X transition, reflecting the fact that the stimulated emission cross section for the latter is relatively large. This suggested the possibility of simultaneous laser oscillation on both the B→X and C→A XeF excimer transitions. In order to investigate the feasibility of simultaneous oscillation on both XeF excimer transitions, a dual wavelength resonator was designed using mirrors that were highly reflective at 351 nm as well as as in the blue-green region near 480 nm. Although conditions were far from optimum in our first tests, laser oscillation on both XeF excimer transitions was routinely observed. Moreover, gas mixture refinement permitted relatively efficient simultaneous UV/visible laser oscillation.

Figure 3 shows the XeF UV/visible laser pulse energy density as a function of Kr pressure for representative conditions. With no Kr in the mixture oscillation on the 351 nm UV B→X transition alone is observed. As the Kr pressure is increased the B→X output decreases gradually in response to the increasing importance of competitive KrF and Kr_2F reactions. However, the presence of Kr significantly reduces absorption in the blue-green region (Ref. 3). The resultant increase in XeF(C→A) gain with increasing Kr pressure, combined with the decreasing competitive B→X oscillation, leads to a gradual increase in the energy of the broadband C→A output centered at about 480 nm, which becomes equal to that of the UV transition for a Kr pressure of about 200 Torr. The spectral plot for a Kr pressure of 200 Torr is shown in Fig. 4.

The dashed line in Fig. 3 shows that the combined UV/visible output exceeds 0.5 J/liter throughout the entire range of Kr pressures, corresponding to an intrinsic efficiency of approximately 1% for the conditions of this experiment. Substantial future increases in both laser energy and efficiency appear likely.

b. Dual UV Wavelength Rare Gas Halide Lasers

The results described above show that an electron beam excited medium optimized for efficient blue/green XeF(C→A) laser oscillation also exhibits strong net gain on the UV B→X transition, and that efficient, simultaneous laser oscillation on both transitions is possible with Kr in the gas mixture. In that work the intensity of the 248 nm KrF(B→X) fluorescence was observed to be comparable to that of the 351 nm XeF(B→X) fluorescence, under conditions for which the dual XeF B→X and C→A laser output energies were approximately equal. Since the

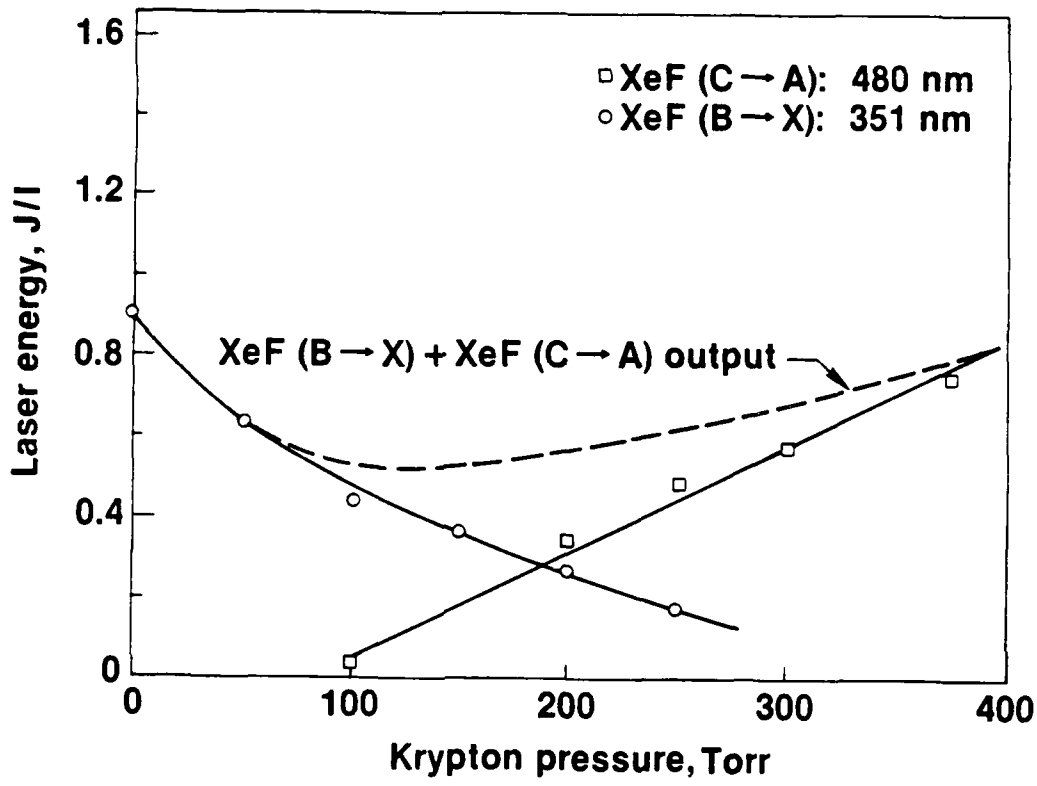

Fig. 3 Time integrated UV/visible XeF laser pulse energy density as a function of Kr pressure for representative e-beam conditions. The gas mixture was comprised of 6.5 atm Ar, 8 Torr Xe, 8 Torr NF_3, and 1 Torr F_2. A stable resonator was used having an output mirror transmissivity of 20% at 351 nm and 8% at 480 nm.

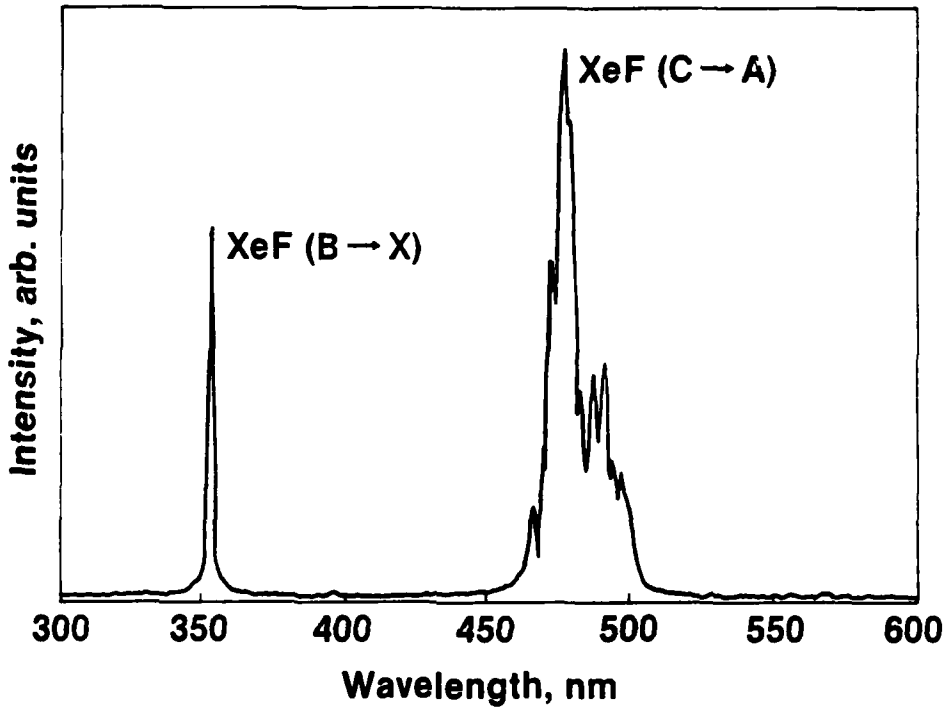

Fig. 4 Time integrated spectra of the XeF B→X laser at 351 nm and C→A laser at ~ 480 nm for the conditions of Fig. 3.

kinetics of the B→X transitions of KrF and XeF are actually less competitive than those of the XeF B→X and C→A transitions, this observation suggested that efficient, simultaneous multiple UV wavelength oscillation on B→X rare gas halide transitions should be possible using appropriate gas mixtures.

In order to investigate the possiblity of simultaneous "dual" UV wavelength laser operation an unmodified discharge excited commercial excimer laser was used (Ref. 6). To obtain dual wavelength oscillation on the KrF and XeF transitions, xenon was added gradually to the three component He-Kr-F_2 mixture that had been optimized for 248 nm KrF laser oscillation alone. A similar experiment was carried out starting with a mixture optimized for 193 nm ArF oscillation; in this case Kr was added gradually to the optimum He-Ar-F_2 mixture. The results of these experiments are shown in Fig. 5.

As xenon is added to the mixture optimized for KrF laser oscillation, the total laser output energy first decreases to a value about one tenth the initial value typical of KrF alone. A minimum in the total energy is established for a xenon pressure of about 14 mbar, above which the total energy increases (Fig. 5). Spectrally resolved data show that initially the KrF laser energy of 248 nm decreases with increasing xenon pressure. However, for xenon pressures between 10 and 15 mbar, both the 248 nm KrF and the 351 nm XeF transitions exhibit laser action simultaneously. At a xenon pressure of ~ 14 mbar the energy of each laser is 10 to 15 mJ resulting in a total combined energy of about (25 ± 10) mJ, corresponding to an overall efficiency of ~ 0.2% based on the energy stored in the capacitors. For xenon pressures above 15 mbar the laser operates only on the 351 nm XeF transition, achieving an output energy at 20 mbar with a non optimized four component mixture that approaches the maximum value that can be obtained using an optimized three component XeF laser mixture. Figure 5 shows that generally similar behavior was also observed for dual ArF (193 nm)/KrF (248 nm) laser oscillation upon addition of Kr to an optimized three component ArF laser mixture. Since no effort was made to optimize the fractional concentrations of the constituents of the four component mixtures of Fig. 5, it seems certain that significantly higher dual laser energy could be achieved with mixture reoptimization, and/or that the output from four component mixtures optimized for a single UV laser wavelength alone might actually be higher than that obtainable using the usual three component mixtures (Ref. 6).

C. Future Directions

The work summarized in the previous paragraphs and in Ref. 4 (see Sec. II) has shown that narrow spectral output combined with efficient energy extraction can be obtained using an XeF(C→A) laser medium to amplify an injected dye laser pulse. These results indicate that efficient, narrow spectral output should be attainable throughout the entire blue-green region using an injection controlled, electrically excited XeF(C→A) medium, with the medium serving either as an amplifier as in the present experiments or as an injection locked oscillator.

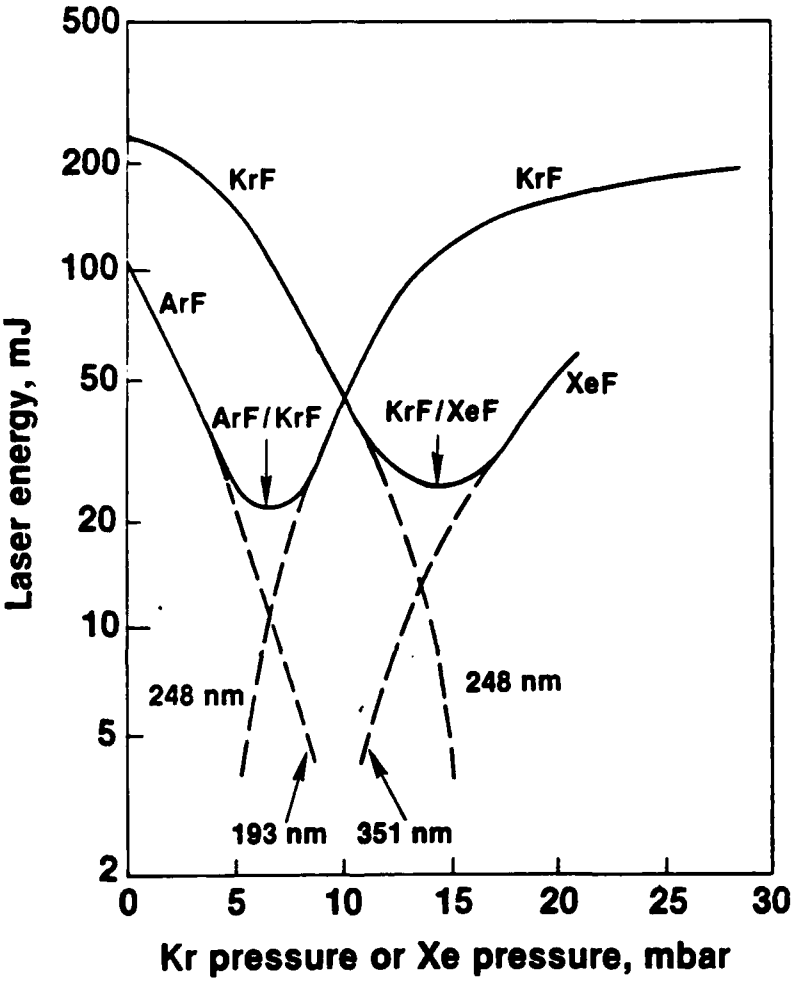

Fig. 5 Total UV laser pulse energy for an ArF/KrF laser as a function of Kr pressure and for a KrF/XeF laser as a function of Xe pressure. The initial gas mixture for the ArF/KrF laser was comprised of 2.2 bar He, 350 mbar Ar, and 7.5 mbar F_2; and for the KrF/XeF laser the initial mixture was comprised of 2.5 bar He, 150 mbar Kr, and 6 mbar F_2. The laser used in these experiments was an unmodified Lambda-Physik model EMG 101 operating at a repetition frequency of a few Hz and a discharge voltage of 30 kV (see Ref. 6 for details).

Demonstration of efficient spectral tuning of the XeF(C→A) laser is a primary objective for 1986. Following the procedures described in detail in Section II (Ref. 4) the wavelength of the injected dye laser pulse will be varied from 450 nm to 520 nm. Measurements show that the net gain exceeds 2% cm^{-1} throughout this entire wavelength range, exhibiting a broad maximum of 3% cm^{-1} centered at ~ 485 nm. Thus, we have a high confidence level that efficient tuning of the XeF(C→A) laser will be possible.

In the XeF(C→A) laser experiments carried out to date an Ar background gas pressure in excess of 5 atm has been used in order to ensure a high level of energy deposition by the e-beam and, of equal importance, to provide rapid XeF B→C mixing and vibrational relaxation. However, our recent experience indicates that it may be possible to achieve the required degree of B→C mixing/vibrational relaxation using a He buffer at much lower pressure, provided other mixture constituents and their partial pressures are judiciously selected. Such a mixture would be compatible with stable electric discharge excitation, a very important consideration. During the next year efforts will be made to demonstrate discharge excitation of the XeF(C→A) laser while retaining the efficiency levels that have become typical of e-beam excitation.

As regards simultaneous, dual UV wavelength laser oscillation and/or UV/visible wavelength operation of rare gas halide laser systems, we believe that there are varied applications in such areas as spectroscopy, optical diagnostics, electronics, materials processing, and medicine for which this unique capability may prove advantageous. Efforts are underway to specifically identify such applications.

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6. Sauerbrey, R. A., W. L. Nighan, F. K. Tittel, W. L. Wilson, Jr. and J. Kinross-Wright; IEEE J. Quantrum Electron. (To be published, February 1986.)

II. REPRINTS OF RECENTLY PUBLISHED PAPERS

- "Efficient Narrow Spectral Output in the Blue-Green Region from an Injection-Controlled Electron Beam Excited XeF(C→A) Laser", by G. Marowsky, N. Nishida, H. Stiegler, F. K. Tittel, W. L. Wilson, Jr., Y. Zhu and W. L. Nighan, Applid Physics Letters, Vol. 47, pp. 657-660, October 1, 1985.

- "Simultanous UV/Visible Laser Oscillation on the B→X and C→A XeF Excimer Transitions", by R. Sauerbrey, Y. Zhu, F. K. Tittel, W. L. Wilson, Jr., N. Nishida, F. Emmert, and W. L. Nighan, IEEE Journal of Quantum Electronics, Vol. QE-21, pp. 418-420, May 1985.

Efficient narrow spectral output in the blue-green region from an injection-controlled electron-beam excited XeF ($C \rightarrow A$) laser

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Efficient, narrow spectral output has been achieved by injection control of an electron-beam excited XeF ($C \rightarrow A$) laser medium using a 482-nm dye laser pulse having a spectral width of 0.01 nm. The energy density and intrinsic efficiency characteristic of the amplified output beam were 3 J/l and approximately 2.5%, respectively, and the spectral width was on the order of that of the injected pulse.

In recent years narrow bandwidth ($\lesssim$ 0.01 nm), tunable laser operation has been demonstrated by injection locking electrically excited rare gas-halide lasers such as KrF (248 nm)[1] and XeF (351 nm),[1,2] and HgBr (502 nm).[3] Additionally, the UV output of lasers such as XeCl (308 nm) has been Raman converted to several specific wavelengths in the visible region, also with narrow spectral width.[4] Although the high efficiency (>1%) typical of these lasers operating as free-running oscillators was preserved in the narrow wavelength-tuned output, their tuning *range* is limited to about 1

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nm. In contrast, the very broadband XeF ($C \rightarrow A$) laser, centered in the blue-green region at 485 nm, has been tuned continuously from about 450 to 510 nm with a spectral width on the order of a few nanometers, using either intracavity optical elements[5,6] or dye laser pulse injection.[7] However, in these experiments both the free-running and tuned laser output were extremely inefficient ($\ll 1\%$).

Recently, very significant improvement in the performance of an electron-beam (e-beam) excited XeF ($C \rightarrow A$) laser has been achieved by selective tailoring of the gas mixture so as to minimize transient absorption.[8-10] Use of multicomponent gas mixtures comprised either of Ar-Xe-F_2-NF_3 (Refs. 8 and 9) or of Ar-Kr-Xe-F_2-NF_3 (Ref. 10) has resulted in laser pulse energy density values in the 1.5–3.0 J/l range with an intrinsic efficiency of approximately 1.5%, a performance level which, for the first time, is comparable to that typical of the $B \rightarrow X$ rare gas-halide and mercury-halide lasers. In these studies the free-running XeF ($C \rightarrow A$) laser output was centered at 480 nm with a bandwidth of ~ 25 nm (FWHM). However, measurements[9,10] showed that the gain extended over a much larger spectral range and exhibited a relatively weak dependence on wavelength. These results indicate that it should be possible to tune the XeF ($C \rightarrow A$) laser continuously throughout the entire blue-green region, with narrow spectral width and with an efficiency typical of that demonstrated in the free-running mode. In this letter we report efficient (~ 2.0–3.0%), narrow spectral output ($\Delta\lambda \sim 0.01$ nm) from an XeF ($C \rightarrow A$) laser medium by amplification of an injected dye laser pulse.

Transverse laser excitation was provided by an e-beam with an electron energy of 1 MeV and a pulse duration of 10 ns (FWHM). The e-beam current density at the center of the optical axis was ~ 200 A cm^{-2}, as measured with a Faraday probe. Specific details of the experimental arrangement and related diagnostic apparatus are described in Ref. 9. For the present purposes the gas mixture was composed of 6.5 atm Ar, 16 Torr Xe, 8 Torr F_2, and 8 Torr NF_3. Good mixing of the component gases and thorough fluorine passivation of the stainless steel reaction cell were found to be absolutely essential in order to ensure reliable laser performance. The source of the injected radiation was a narrow bandwidth excimer-pumped dye laser system (Lambda-Physik models EMG 100 and FL 2002). This reference oscillator arrangement delivered up to 12 mJ in a 10 ns pulse, tunable from 440 to 540 nm using Coumarin dyes 47, 102, and 307. The spectral width of the seed pulse was 0.01 nm as measured with a monitoring étalon.

The collimated dye laser pulse was injected through a small hole (2 mm diameter) in the concave back mirror of an intracell positive branch confocal unstable resonator[1] as illustrated in Fig. 1. Two different resonators were used having radii of curvature for the concave mirrors of either 1.5 or 2.0 m, and for the corresponding smaller convex mirrors of either 1.22 or 1.75 m; the mirror separation was about 13.0 cm, depending on the specific resonator. The concave mirrors were covered with a broadband coating that was totally reflective from 440 to 530 nm, while the coating on the convex output reflector (a meniscus lens) was limited to a diameter of 1.4 cm. The thin outer annular region of the output

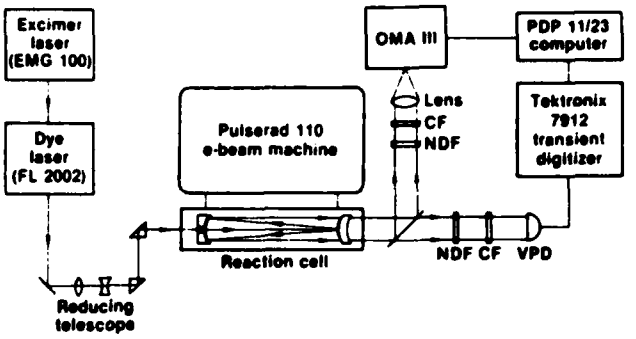

FIG. 1. Schematic illustration of experimental arrangement. NDF = neutral density filter, CF = color-glass filter, VPD = vacuum photodiode.

mirrors was AR coated on both sides. These elements resulted in cavity magnification (M) values of 1.23 and 1.14, corresponding to output coupling of 34 and 24%, respectively, values that are very much higher than the $\sim 5\%$ previously found to be optimum for a free-running stable resonator.[9,10] Since oscillation in this type of unstable resonator builds up most readily in the "lossless" paraxial region,[1] and since (for these small magnifications) the injection hole constitutes a large loss ($\sim 70\%$) to the paraxial volume, significant self-oscillation (injected or not) is not possible. Indeed, the output energy obtained by operating these resonators as free-running oscillators was three to four orders of magnitude lower than that obtained using an optimized stable resonator under otherwise similar conditions.[10] Thus, in this case the primary role of the cavity is to serve as the beam-expanding telescope of a regenerative amplifier. Hence the term *injection controlled* is used instead of injection locked.

The temporal relationships among the injected 482-nm dye laser pulse, the e-beam excitation pulse, the XeF ($C \rightarrow A$) laser output at 482 nm, and the free-running broadband XeF ($C \rightarrow A$) laser output are shown in Fig. 2. Also shown for

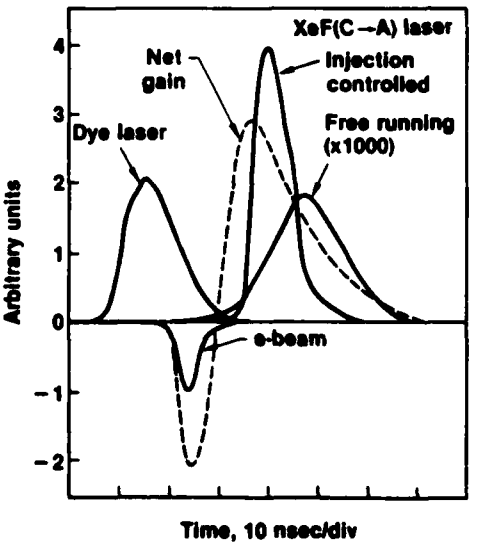

FIG. 2. Approximate temporal relationships among the 482-nm injected dye laser pulse at the cavity input hole, the e-beam excitation pulse, the 482-nm XeF ($C \rightarrow A$) laser output at the cavity exit, and the broadband free-running XeF ($C \rightarrow A$) laser output. Also shown is the typical temporal evolution of the zero field net gain at 488 nm. For the present mixture, 6.5 atm Ar, 16 Torr Xe, 8 Torr NF_3, and 8 Torr F_2, the peak gain is $\sim 2.75\%$ cm^{-1} (Ref. 10).

illustrative purposes is the temporal evolution of the *net* gain at 488 nm. The causes of the strong initial absorption occurring during the e-beam excitation pulse have been identified and are explained in detail elsewhere.[9,10] Because of the low magnification, it takes ~10 round trips through the ~13-cm-long cavity before the injected dye laser pulse expands to fill the active cavity volume, requiring a time of ~10 ns. Thus, the duration of the injected pulse, the rise time and the duration of the gain, and the cavity fill time are all about the same. For this reason, the timing of the dye laser pulse with respect to the firing of the *e*-beam was found to be quite critical and had to be controlled to within a few nanoseconds in order to obtain repeatable results.

Figure 3 shows the dependence of the XeF ($C \rightarrow A$) output pulse energy on the energy of the injected dye laser pulse for the $M = 1.23$ cavity. Because of the low magnification, in the *absence* of *e*-beam excitation 60 to 70% of the dye laser energy is reflected back out through the 2-mm-diam hole in the concave mirror. The fraction of the input pulse that escapes through the hole when the *e*-beam *is* fired is likely to be somewhat lower due to spatial nonuniformity of the gain medium. Thus, the input energy shown in Fig. 3 represents an upper limit to the actual intracavity value, and the output-input ratio that can be inferred from the data is therefore a lower limit. The linear dependence of the output pulse energy on dye laser input energy for a three order of magnitude variation of the latter indicates that the cavity/medium combination is acting as a multipass amplifier for the present conditions and that the gain is not significantly saturated until high input energies are reached. Such behavior is consistent with the very low output obtained with the resonator operating as a free-running oscillator. However, saturation of the gain medium appears to occur for input pulse energies above approximately 0.1 mJ. The 20-mJ maximum output for the $M = 1.23$ cavity corresponds to an energy density of 1 J/l and an intrinsic energy utilization efficiency of approximately 1%, based on an active volume of 20 cm^3 and an *e*-beam energy deposition of ~100 J/l.[9] For the same conditions the $M = 1.14$ cavity resulted in an output energy an order of magnitude higher than the $M = 1.23$ cavity when the input energy was <0.01 mJ, with a maximum output of over 60 mJ at saturation, corresponding to energy density and intrinsic efficiency values of 3 J/l and approximately 2.5%, respectively.[11] For the net gain typical of these conditions (Fig. 2) the significantly increased output obtained using the $M = 1.14$ cavity compared to that of the $M = 1.23$ cavity is consistent with the ~50% longer amplification path length of the former.

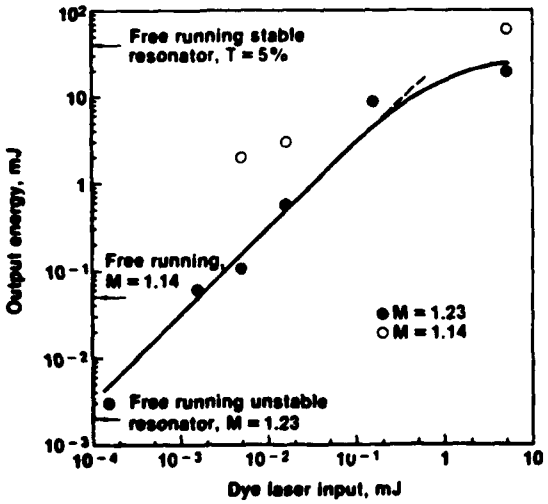

FIG. 3. XeF ($C \rightarrow A$) output pulse energy dependence on the injected dye laser energy, both at 482 nm, measured using a calibrated vacuum photodiode detector. The gas mixture was comprised of 6.5 atm Ar, 16 Torr Xe, 8 Torr NF_3, and 8 Torr F_2; and volumetric *e*-beam energy deposition was ~100 J/l (Ref. 9). Laser output levels obtained with unstable and stable (optimized) free-running oscillators are indicated

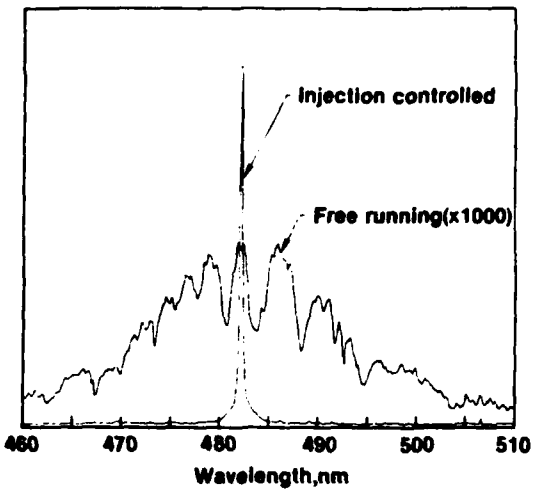

FIG. 4. XeF ($C \rightarrow A$) spectra for the free-running and injection-controlled conditons of Fig. 3. The resolution limit of the measurement system was 0.5 nm.

Presented in Fig. 4 is the broadband XeF ($C \rightarrow A$) spectrum typical of the unstable (or stable[9,10]) resonators operating as free-running oscillators, compared with that of the injection-controlled XeF ($C \rightarrow A$) amplifier. The indicated ~0.5-nm width of the amplified 482-nm pulse reflects the resolution limit of our present measurement system. Preliminary evaluation of the spectral characteristics of the narrowed XeF ($C \rightarrow A$) output indicates that the spectral width is nearly the same as that of the dye laser input, i.e., $\Delta\lambda \sim 0.01$ nm. In these experiments the dye laser output was tuned so as to coincide with a maximum in the free-running laser spectrum (Fig. 4). However, tuning the input a few nanometers to the location of an absorption valley resulted in no significant changes in the output. Although the broadband laser spectrum of a free-running oscillator (stable or unstable) typically is limited to the 465–495-nm range within which the gain is a maximum, measurements show[9,10] that the net gain is reduced from its maximum at ~485 nm by only ~20% for wavelengths as low as 460 nm and as high as 510 nm, indicating that continuous tuning over a broad range with high-energy output should be possible.

This investigation has shown that simultaneous narrow spectral output and efficient energy extraction can be obtained using an XeF ($C \rightarrow A$) laser medium to amplify an injected dye laser pulse. These results indicate that *efficient*, narrow spectral output should be attainable throughout the entire blue-green region using an injection-controlled, elec-

trically excited XeF ($C \rightarrow A$) medium, with the medium serving either as an amplifier as in the present investigation or as an injection-locked oscillator. However, longer gain lengths will be required for true efficient oscillator operation of an unstable cavity.

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[11]In the work reported herein only Ar-Xe-NF_3-F_2 mixtures were used. Five component mixtures containing Kr require nearly an order of magnitude less F_2 for optimum performance, a factor which complicates the passivation procedure for the present apparatus. Nonetheless, the magnitude of the net gain is significantly larger and its duration longer for Kr-containing mixtures than is the case for the mixture used in the present work (Ref. 10). This indicates that much higher levels of output energy/efficiency should be attainable with no increase in either the energy of the injected input pulse or the e-beam excitation pulse.

Simultaneous UV/Visible Laser Oscillation on the $B \rightarrow X$ and $C \rightarrow A$ XeF Excimer Transitions

ROLAND SAUERBREY, YUNPING ZHU, FRANK K. TITTEL, WILLIAM L. WILSON, JR., N. NISHIDA, F. EMMERT, AND WILLIAM L. NIGHAN

Abstract—Simultaneous laser oscillation from the 351 nm XeF($B \rightarrow X$) transition and the broad-band XeF($C \rightarrow A$) transition centered near 475 nm has been demonstrated using intense, short-pulse electron-beam excitation of high-pressure gas mixtures. Analysis of the causes of transient absorption suggests that it may be possible to obtain efficient UV/visible laser oscillation from each of the XeF excimer transitions excited in the same medium.

Introduction

XENON fluoride is the only diatomic rare gas-halide molecule exhibiting two lasing transitions. Laser oscillation occurs on the $B(\frac{1}{2})$-$X(\frac{1}{2})$ transition in the near ultraviolet at 351 nm, and on the broad-band tunable $C(\frac{3}{2})$-$A(\frac{3}{2})$ transition in the visible centered near 475 nm. Electrically excited lasers operating on the $B \rightarrow X$ transition have been under investigation for several years, and are capable of very efficient (~2-5 percent) generation of high-power UV radiation [1]. Recently, efficient (>1 percent) operation of the XeF($C \rightarrow A$) laser with an energy output in excess of 3 J/l was also demonstrated [2], [3]. For a variety of applications such as frequency mixing or multistep photoexitation, it might be of interest to have an efficient laser source that is capable of emitting intense UV *and* tunable visible radiation simultaneously. In this letter, the feasibility of simultaneous operation of the XeF($B \rightarrow X$) and ($C \rightarrow A$) laser transitions in the same apparatus is reported for the first time.

Experimental Apparatus and Procedure

A gas mixture comprised of 8 torr F_2, 8 torr NF_3, 16 torr Xe, and 6.5 atm Ar was excited by an intense electron beam (1 MeV, 250 A · cm^{-2}, 10 ns FWHM), conditions previously found to be compatible with efficient XeF ($C \rightarrow A$) laser operation [2]. In order to investigate the possibility of simultaneous laser oscillation on both XeF excimer transitions, a dual-wavelength resonator was constructed using broad-band mirrors that were available in our laboratory. The basic design of this resonator is shown in Fig. 1. A curved mirror with more than 99 percent reflectivity between 350 and 490 nm was used as the full reflector. Two flat output couplers were mounted as shown. The broad-band $C \rightarrow A$ output coupler had a reflectivity of 98 percent at a wavelength of 510 ± 30 nm and a transmissivity of 90 percent for 351 nm radiation, while the $B \rightarrow X$ output mirror had a reflectivity of 83 percent for the UV radiation and 60 percent transmissivity in the visible region. Between these two mirrors, a viton O-ring was inserted and, by means of a set of three adjustment screws, the $C \rightarrow A$ mirror was aligned so as to be parallel to the $B \rightarrow X$ mirror. Alignment was performed before the mirrors were installed in the reaction cell. Both mirror holders could then be aligned externally as described in [2]. The dual-wavelength resonator so constructed had relatively small intracavity losses for the $C \rightarrow A$ transition, while those for the $B \rightarrow X$ transition were quite high. However, the gain of the narrow-band UV bound-bound transition is considerably larger than that of the $C \rightarrow A$ transition, since the $B \rightarrow X$ stimulated emission cross section is about 30 times larger than that of the $C \rightarrow A$ transition.

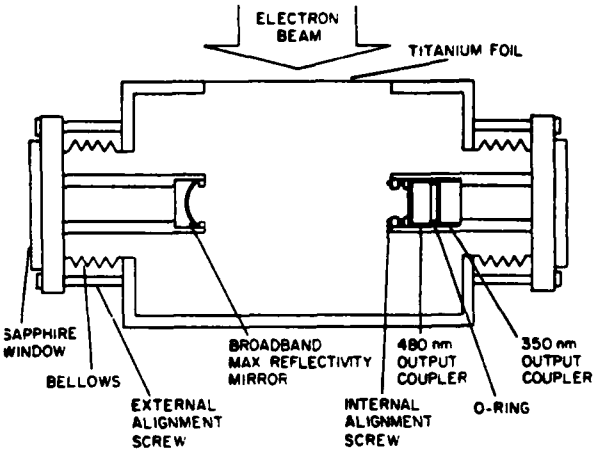

Fig. 1. Dual wavelength resonator configuration for the simultaneous operation of the XeF($B \rightarrow X$) and XeF($C \rightarrow A$) lasers.

Results and Analysis

Although the gas mixture was far from optimum for $B \rightarrow X$ laser oscillation [1], and the $C \rightarrow A$ resonator was not optimized, laser oscillation on both transitions was routinely observed. Presented in Figs. 2 and 3 are the temporal and spectral characteristics of the UV and blue/green XeF $B \rightarrow X$ and $C \rightarrow A$ laser pulses obtained using the dual, coincident UV/visible cavity configuration illustrated in Fig. 1. As described

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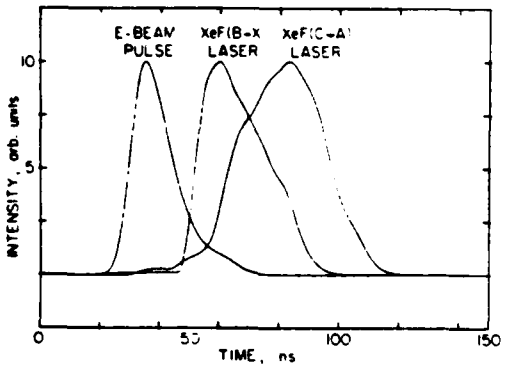

Fig. 2. Temporal evolution of the *e*-beam pulse and the XeF($B \rightarrow X$) and XeF($C \rightarrow A$) laser pulses for a mixture comprised of 6.5 atm Ar, 16 torr Xe, 8 torr F_2, and 8 torr NF_3.

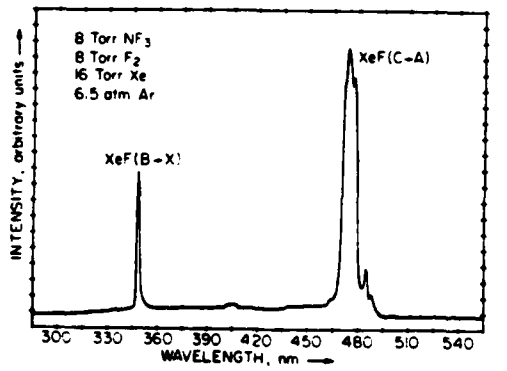

Fig. 3. Time integrated spectrum of the XeF $B \rightarrow X$ laser at 351 nm and $C \rightarrow A$ laser centered near 475 nm.

previously [2], the *e*-beam pulse results in the production of broad-band absorbing species, and therefore, the laser pulses appear in the afterglow regime (Fig. 2). The net effect of transient absorption is most severe for the $C \rightarrow A$ transition due to the fact that its cross section for stimulated emission is relatively small ($\sim 10^{-17}$ cm^2) [4]. Thus, the onset of the $C \rightarrow A$ laser pulse is delayed for a longer time than that of the $B \rightarrow X$ pulse.

The laser spectrum (Fig. 3) shows both the narrow $B \rightarrow X$ emission at 351 nm and the broad-band $C \rightarrow A$ emission centered near 475 nm. The laser wavelength and spectral width for the $C \rightarrow A$ transition are mainly determined by the specific properties of the end reflector and output coupler. For the present nonoptimized dual-wavelength resonator, the laser pulse energy levels were relatively low; ~0.01 J/l was obtained from the $C \rightarrow A$ transition and ~0.05 J/l for the $B \rightarrow X$ transition. However, for these specific conditions, $C \rightarrow A$ laser pulse energy in excess of 1.0 J/l has been routinely obtained using an optimized resonator [3].

Presented in Fig. 4 is the temporal evolution of the various contributions to the gain and absorption at 351 and 475 nm, computed for the conditions of Figs. 2 and 3 following the procedures described in detail in [2]. The *net* gain shown for the blue-green $C \rightarrow A$ transition is in very good agreement with experimental observations [2], [3]. We have not measured the gain/absorption in the UV region. However, the results

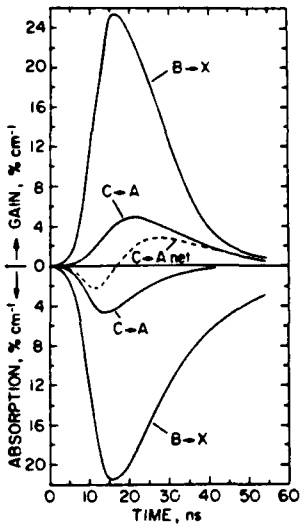

Fig. 4. Contributions to the XeF($B \rightarrow X$) and XeF($C \rightarrow A$) gain and absorption at 351 and 475 nm, respectively, computed for the conditions of Figs. 2 and 3 following the procedures described in [2].

of Fig. 4 show that the computed *net* gain for the UV $B \rightarrow X$ transition (~4 percent cm^{-1} maximum at ~15-20 ns) is the difference between two much larger gain-absorption values. For these specific mixture conditions, which have been optimized for blue-green $C \rightarrow A$ laser oscillation, the calculations show that absorption in the UV is dominated (>75 percent) by Ar_2F photodissociation [5]. Krypton has been found to be an effective quenching species for Ar_2F [6]. Moreover, subsequent to the completion of this work, it was found that the addition of Kr at partial pressures in the 0.5-1.0 atm range results in an increased rate of XeF(B, C) formation and in a decrease in absorption in the visible region, the combined effect of which is a significant increase in *net* gain for the $C \rightarrow A$ transition [3]. For these reasons, mixtures containing Kr might exhibit higher levels of net gain for *both* the $B \rightarrow X$ and $C \rightarrow A$ transitions than those indicated in Fig. 4. This suggests that significantly higher $B \rightarrow X/C \rightarrow A$ dual laser output may be possible.

Summary

We have demonstrated that an *e*-beam excited medium that has been optimized for efficient blue/green XeF($C \rightarrow A$) laser oscillation also exhibits strong net gain for the UV $B \rightarrow X$ transition, and that simultaneous laser oscillation on both transitions is possible. Further, our results show that the presence of a strong $B \rightarrow X$ flux has relatively little effect on $C \rightarrow A$ gain. These findings suggest that with an optimum resonator design and/or with additional mixture refinement, efficient ($\lesssim$1 percent) UV/visible laser oscillation from *each* of the XeF excimer transitions excited in the same medium may be possible.

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